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Wind resource evaluation in São João do Cariri (SJC) – Paraiba, Brazil

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ABSTRACT

In this study wind resources evaluation and wind energy assessment of the São João do Cariri (SJC) in Paraiba (PB) state situated in Brazilian northeast were analyzed during the period 2006/2009. Wind speed (V, m/s), wind direction and air temperature (T, °C) at 25 m and 50 m were collected from SONDA (Sistema de Organização Nacional de Dados Ambientais) meteorological station (38°N 7°E). The average wind speed and temperature for 25 m and 50 m were found 4.74 m/s, 24.46 °C and 5.31 m/s 24.25 °C respectively. The wind speed predominate direction found were SSE (165°) from both 25 m and 50 m heights. The wind speed distribution curve was obtained using the Weibull probability density function through the WAsP program, the values of Weibull shape (K), scale (A, m/s) and Weibull fit wind speed and power wind density (P, W/m^2) were found 2.54, 5.4 m/s, 4.76 m/s and 103 W/m^2 for 25 m wind height measurements and 2.59, 6.0 m/s, 5.36 m/s and 145 W/m^2 for 50 m wind height measurements. The cost (€/kWh) from electrical wind energy obtained by wind turbine generation, at 25 m height, was found 0.046 by using 300 kW power rated wind turbine, in the best scenario, with an associate C_f of 14.5%.

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1. Introduction

Wind energy is one of the most usage forms of renewable energy, according to [1], in 2008 the world celebrated the 100 GW mark in total installed wind energy capacity, in this scenery, USA (20.8%), German (19.8%), Spain (13.9%), China (10.1%) and India (8.0%) are the top five countries in wind energy capacity installed up to year 2008, in another hand USA (30.8%), China (23.3%), India (6.7%), Germany (6.2%) and Spain (5.9%) were the top five countries in new wind resources system installed during calendar year 2008.

Brazil has a total of 104.7 GW [2] of installed power, 68.9% of this amount (energy matrix), comes from hydraulic resources and only 0.395% (414.000 kW) from wind energy resources. The first Brazilian wind atlas, published by CEPEL/ELETROBRAS (Centro de Investigaçâo Elétrica/Compania Eletrica Brasileira) in 2001 shows that the potential for onshore wind energy capacity is 143 GW in Brazil (at 50 m high) and the best wind resources in terms of wind speed and capacity factor are in the Northeast, Southeast and Southern regions [3].

In order to stimulate new wind power projects, PROINFA (Programa de Incentivo às Fontes Alternativas de Energia Elétrica) was established by the Brazilian Congress as a two-phase, long-term program. The selection bidding process required some of the main pre-requisites for financing the projects: environmental licenses, qualified wind measurements, land clearance through lease or property ownership, etc. The 20 year power purchase contracts with ELETROBRAS have energy prices ranging from €77 to €87/MWh (equivalent to R$212 to R$241/MWh) in March 2007, depending on the capacity factor of the project. In PROINFA's first

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phase (PROINFA I), as of December 2006, 208 MW of wind energy projects are commissioned (159 MW in South, 49 MW in Northeast Brazil) [4].

2. The wind characterization and potential assessment review

The wind characterization in terms of speed, direction and wind power is the first step to obtain the initial feasibility of generating electricity from wind power through a wind farm, in a given region. In the wind energy literature, many relevant works have been developed in this aim. Rio and Simoes [5] studied monthly forecasts of the average wind speed in Portugal and Cadenas et Rivera [6] in the south coast of Oaxaca, Mexico using the Autoregressive Integrated Moving Average (ARIMA) and Artificial Neural Networks (ANN) methodologies for the treatment of wind time series. Serrano et al. [7] studied the wind characteristic and energy potential at Cucuta, Colombia showing the Weibull characteristic parameters to the wind from this region and also the simulation results of wind energy generation by 1.5 MW wind turbine in 3 different heights, Kose et al. [8] and Ucar and Balo [9] investigated the wind characteristics and energy potential in Kutahya and Uludag-Bursa respectively, both in Turkey, Ahmed et al. [10] developed similar work in Pakistan to verify the possible use of wind energy for irrigation deep well pumping and small scale power generation, Zhou et al. [11] in the Pearl River Delta region in China and Elamouria and Ben Amar [12] in Tunisia. Chang et al. [13] present an assessment of wind characteristics and wind turbine characteristics in Taiwan and Fawzi and Jowder [14] did a similar study in the Kingdom of Bahrain utilizing the graphical method and Weibull for the wind statistical study. Bekele and Palm [15] studied the wind energy potential assessment at four typical locations in Ethiopia and Raichle and Carson [16] developed a similar work including an estimation of annual energy outputs from a small wind farm in Southern Appalachian Ridges (USA). Solorzano and Bernat [17] showed in their works the results of statistical analysis of wind power in the region of Veracruz (Mexico) and Cellura [18] et al. did an similar statistical analysis for wind speed spatial estimation in Sicily. Omer [19] reviewed the wind energy resources of Sudan and its application for water pump and Silva et al [20] described the Wind power in the predominant wind direction in Northeast Brazil.

3. SJC meteorological station – SONDA project

São João do Cariri (07°23′27″S; 36°31′58″O) is an ancient city of Paraiba state, located in the semi-arid of northeast region. Founded in 1800, is 458 m above sea level, 216 km away from João Pessoa (Paraiba's state capital) with an estimated population of 4438 habitants and superficial area of 702 km^2.

SJC is one of the Brazilian cities who have a SONDA project base. The wind data used in this project are obtained from SONDA project; the wind speed, wind direction and temperature were taken at height of 25 and 50 m at each 10 min and validate according to SONDA quality project procedures. A total of 35 months of measurements between 2006 and beginning of 2009 in SJC meteorological station (07°22′54″S, 36°31′38″O and altitude of 718 m), were used in the current study.

4. Statistical distribution for wind data

The Weibull law is the most frequently used model to describe the distribution of the wind speed [21,22]. The distribution is also used in other sectors like automotive sector for analysis of survival data [23].

The probability density function (PDF) of the wind speed is given by

$$f(V) = \left(\frac{K}{A}\right)\left(\frac{V}{A}\right)^{K-1} \exp\left(-\frac{V}{A}\right)^{K} \tag{1}$$

where

- $f(V)$ is the probability density function of the wind speed;
- V is the wind speed (m/s);
- A is the Weibull scale parameter (m/s);
- K is the dimensionless Weibull shape parameter.

According the value of K, the Weibull distribution is similar to other kinds of statistical distribution ($K = 1.0$: exponential, $K = 2.0$: Rayleigh, $K = 3.5$: Normal) [24].

The cumulative distribution function $F(V)$ is written as follows:

$$F(V) = 1 - \exp\left(-\frac{V}{A}\right)^{K} \tag{2}$$

The wind power available $P(W)$ that can be obtained in cross sectional area A_T (m^2) circular area created by the wind turbine blades perpendicular to the wind at speed V (m/s) with an given air density ρ (kg/m^3), is given in the following equation:

$$P = \frac{1}{2}\rho_{air} A_T V^3 \tag{3}$$

The amount of power which can be extracted from the wind, depends on the available wind energy and on the operating characteristics of the wind energy extraction device [19]. However, wind machines cannot use 100% of this power due to the Berz limit. The previous equation (3) can be rewrite by adding a coefficient, called C_p, which defined the maximum efficiency of the Betz limit (0.593)

$$P = \frac{1}{2} C_p \rho_{air} A_T V^3 \tag{4}$$

Due to temporal variations of wind, a method to characterize the power wind available at a particular place is given by the average power per unit area exposed to wind, which is independent of the size of the wind turbine, generally called wind power density (P/A_T), expressed in W/m^2 and defined by Eq. (5).

$$\frac{P}{A_T} = \frac{1}{2} C_p \rho_{air} V^3 \tag{5}$$

The wind energy (E) that can be extracted by a wind turbine is defined by the following equation:

$$E = t \int_0^{\infty} P(U) f(V) \mathrm{d}U \tag{6}$$

where

- $f(V)$ is the probability density function of the wind speed;
- $P(U)$ is the power curve of the turbine (W)
- t is the time period (s).

Replacing Eq. (1) into (6), we obtain the wind energy in terms of Weibull distribution.

$$E = t \int \left(\frac{K}{A}\right)\left(\frac{U}{A}\right)^{K-1} \exp\left(-\frac{U}{A}\right)^{K} P(U) \mathrm{d}U \tag{7}$$

The capacity factor (C_f) is one element in measuring the productivity of a wind turbine or any other power production facility. It compares the plant's actual production over a given period of time with the amount of power the plant would have produced if it had

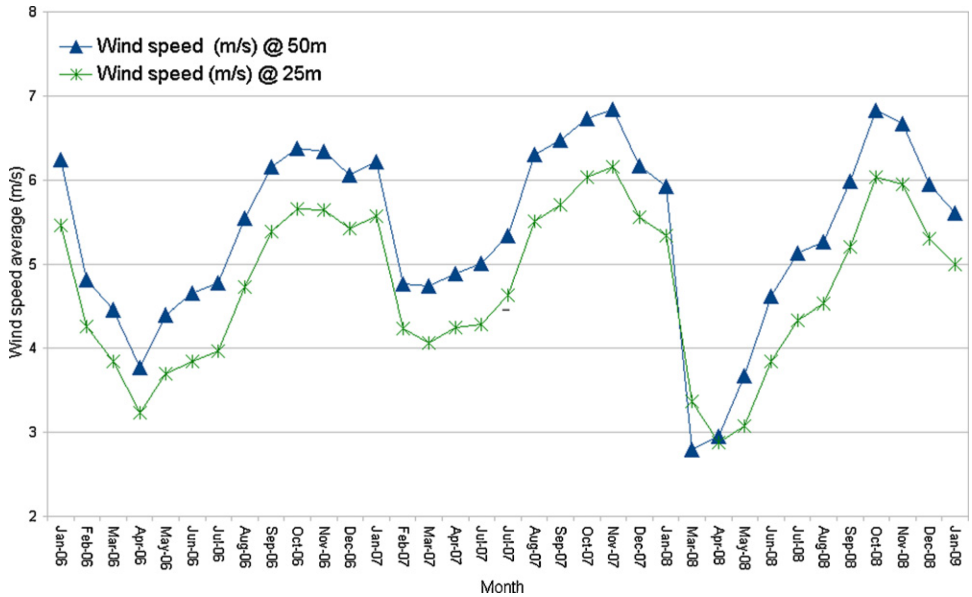

Fig. 1. Monthly wind speed average at 25 and 50 m from SJC meteorological station.

run at full capacity for the same amount of time and is given by the following equation being expressed in %.

$$C_f(\%) = \frac{\text{Wind energy produced (Wh/year)}}{\text{Max wind energy produced (Wh/year)}} \tag{8}$$

An equivalent hour (Eh), expressed in hours, is the parameter used to express wind farms exploitation. It constitutes the equivalent relationship between the operational time of the machine and its nominal potential. The best placed wind frames in Spain register an operational average of 2830 h; some frames exceed 3000 h/year of real generation [25]. The value of Eh is being expressed by the following equation:

$$\text{Eh(h)}(\%) = 8760\text{h}.C_f \tag{9}$$

5. Results and discussion

The data were analyzed using the WAsP program licensed by VIGO University of Spain, during first author master thesis. WAsP is used for predicting wind climates, wind resources, and power productions from wind turbines and wind farms.

The predictions are based on wind data (wind speed, wind direction and air temperature – optional) measured at meteorological stations in the same region in a given altitude (usually 10, 25 and 50 m). The program includes a complex terrain flow model, a roughness change model and a model for sheltering obstacles.

Fig. 1 shows the wind speed profile (monthly average) from SJC at 25 and 50 m heights. The maximum value of wind speed was observed in Nov/07 (6.16 m/s and 6.48 m/s) from heights and the minimum value in April/08 (2.88 m/s) for 25 m and in March/08 (2.78 m/s) for 50 m.

The maximum value of wind temperature found was 26.4 °C and 26.04 °C in Feb/06 for both heights and the minimum value found was 21.68 °C in Jul/08 at 25 m and 25.11 °C in Dec/07 at 50 m height. Fig. 2 shows the wind temperature profile (monthly average) from SJC at 25 m and 50 m heights.

Regarding the wind direction, SJC region has southeast predominant wind direction, as showed in the wind rose in Fig. 3, for 25 m and 50 m heights. The southeast predominant direction is very beneficial to wind energy prospection, because the amount of energy lost by the wind turbines due to the wind direction changes is reduced.

Using the Weibull distribution (1), we obtained the scale (A) and shape (K) parameter for each month (monthly average). Fig. 4 represents the distribution of booths parameters during the studied time period.

The wind power density monthly average estimation is obtained from (5). Fig. 5 represents the monthly power density average distribution through the time period for SJC meteorological station; taken in consideration an constant value of air density ($\rho = 1.225\ \text{kg/m}^3$).

Table 1 presents a resume with all characteristic parameters from SJC wind data analysis.

SJC's wind map region was developed using WAsP program. Figs. 6 and 7 show the wind speed and wind power density map from SJC zone at 25 m height, with a grid of 45 rows × 45 columns with 500 m of resolution, covering an area of 506 km^2 in the boundaries of SJC meteorological station.

Figs. 8 and 9 show the wind speed and wind energy density map from SJC zone at 50 m height, with a grid of 45 rows × 45 columns with 500 m of resolution, covering an area of 506 km^2 in the boundaries of SJC meteorological station.

6. Wind turbines performance assessment

The wind turbines performance assessment was done with the wind data at 25 m height. In this study, 3 different types of wind turbine (from WAsP database) were selected. Table 2 describes the wind turbines key characteristics used in the performance assessment. The wind turbines were placed in the same location than the meteorological station, to improve the reliability of the results.

Table 1
SJC wind data analysis characteristics.

Characteristics	25 m height	50 m height
Wind speed average – V (m/s)	4.74	5.38
Wind air temperature average – T (°C)	24.46	24.25
Air density average (kg/m^3)	1.089	1.114
Weibull Scale parameter – A (m/s)	5.40	6.0
Weibull Shape parameter – K	2.54	2.59
Weibull wind speed – U (m/s)	4.76	5.36
Wind power density – (W/m^2)[a]	103	145

[a] Take in consideration air density = 1.225 kg/m^3.

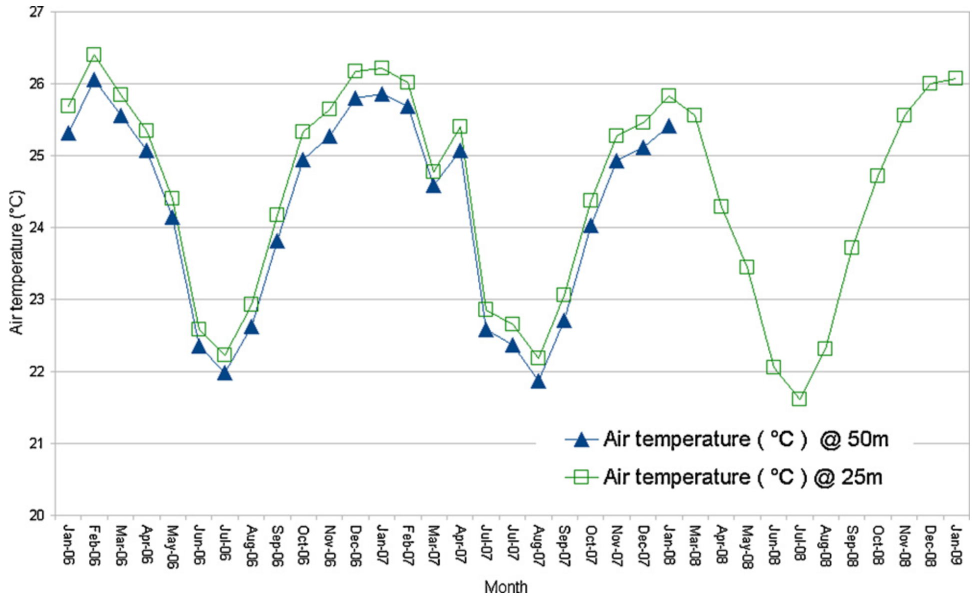

Fig. 2. Monthly wind temperature average at 25 and 50 m from SJC meteorological station.

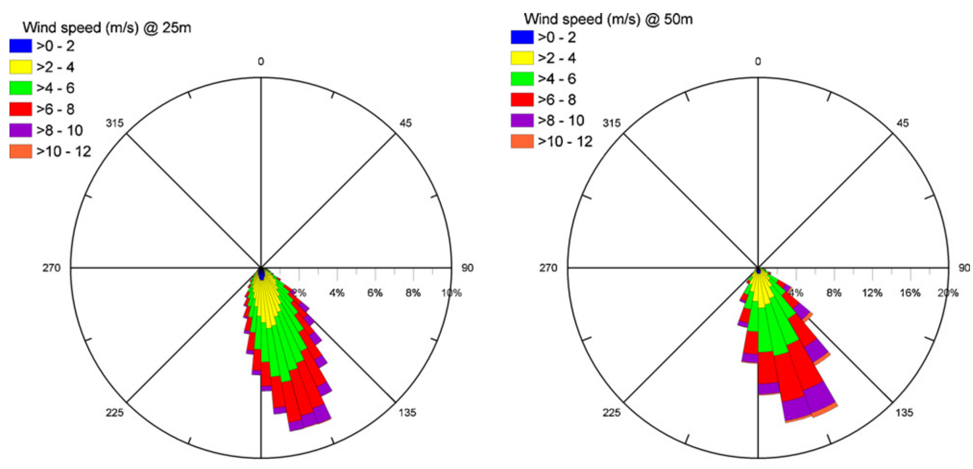

Fig. 3. São João do Cariri wind rose at 25 and 50 m from SJC meteorological station.

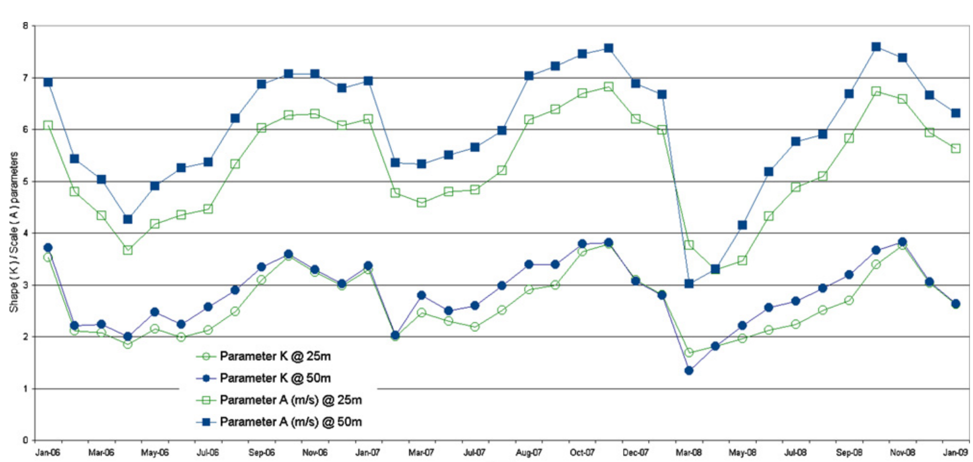

Fig. 4. Monthly shape (K) and scale (A) Weibull parameter average at 25 and 50 m from SJC meteorological station.

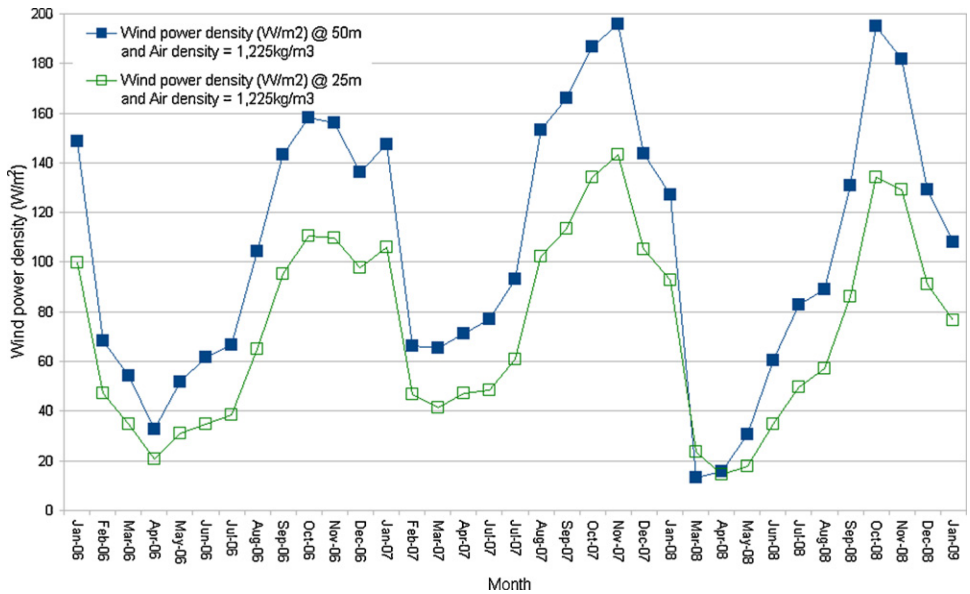

Fig. 5. Monthly wind power average at 25 and 50 m from SJC meteorological station.

Table 2
Wind turbines characteristics.

Turbine name	Turbine ID	Turbine height (m)	Rated power (kW)	Swept area (m^2)	Cut in speed (m/s)	Cut-off speed (m/s)
Bonus Mk III	1	30.0	300	875	3.0	25.0
Vestas V27	2	32.5	225	572	4.0	25.0
Bonus Mk III	3	35.0	450	1075	4.0	25.0

Table 3
Wind turbines assessment results.

Turbine ID	Capacity factor – C_f (%)	Equivalent hours – Eq (h)	AEP Net (MWh)
1	14.5	1274	382.1
2	12.1	1060	238.5
3	12.0	1047	471.2

Table 3 shows the wind turbines characterization results, in terms of Capacity Factor (C_f), Equivalents Hours (h) and Annual energy Produces Net (AEP, MWh).

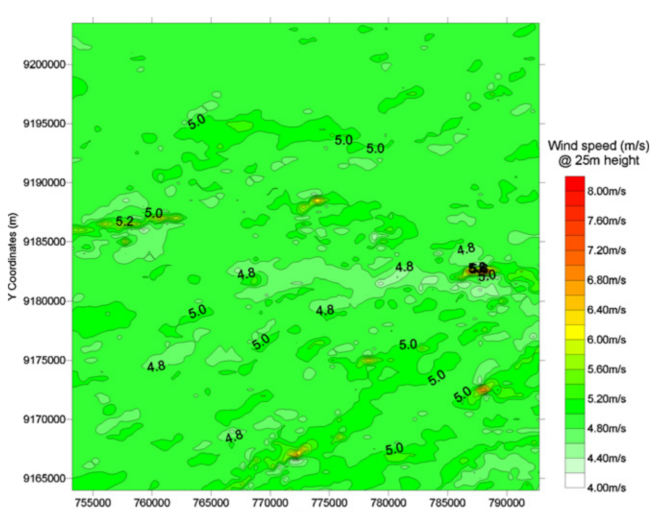

Fig. 6. SJC wind speed map at 25 m (45 rows × 45 columns with 500 m of resolution) covering 506 km^2.

7. Economical assessment

The economical assessment (€/kWh) has been done under the following assumptions:

1. Investment (I) includes the installed turbine price (including civil operations, electrical connections, R&D, etc.) equal 1M€/MW [26].
2. Operation maintenance and repair cost (C_{omr}), expressed in €, were considered to be 25% of the annual cost of the turbine (machine price/lifetime).
3. The interest rate (r) and inflation rate (i) were taken to be 8.75% [27] and 4.7% [28], respectively.

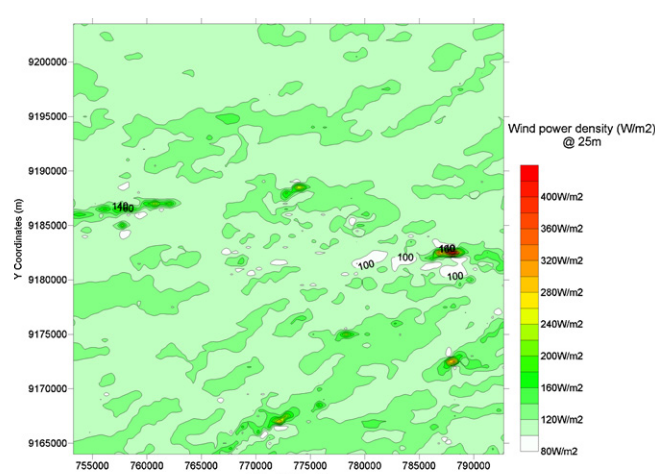

Fig. 7. SJC wind power density map at 25 m (45 rows × 45 columns with 500 m of resolution) covering 506 km^2.

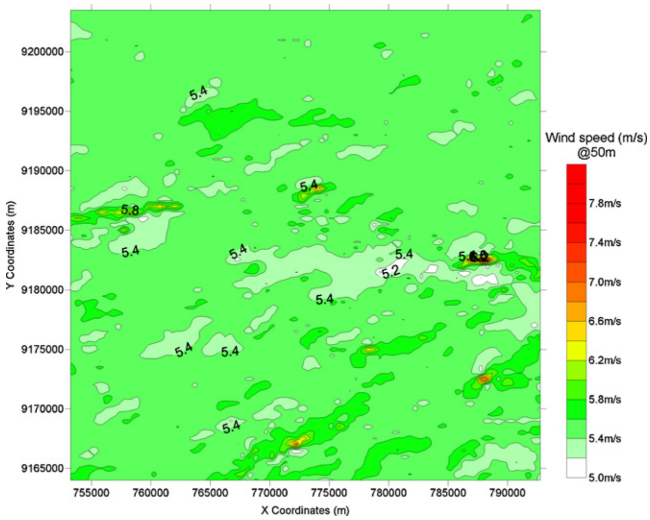

Fig. 8. SJC wind speed map at 25 m (45 rows × 45 columns with 500 m of resolution) covering 506 km^2.

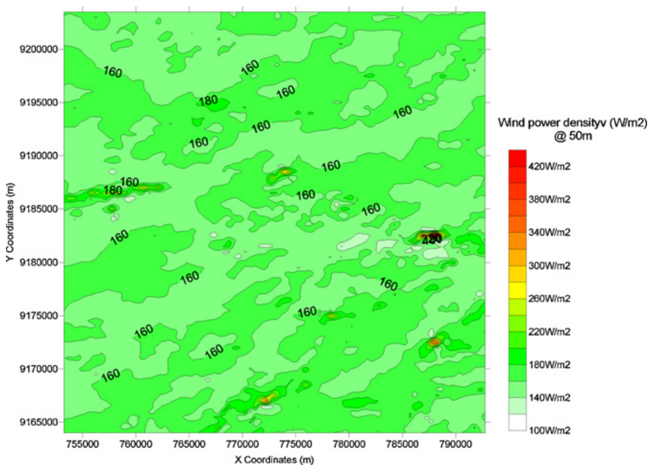

Fig. 9. SJC wind power density map at 50 m (45 rows × 45 columns with 500 m of resolution) covering 506 km^2.

Table 4
Wind turbines assessment results.

Turbine ID	PVC (€)	Energy cost (€/kWh)
1	349.808	0.046
2	262.356	0.055
3	524.712	0.056

4. Scrap value S, expressed in €, was taken to be 10% of the installed wind turbine price (I).
5. The lifetime of the wind turbine (t) was assumed to be 20 years.

The present value of costs (PVC) is

$$\mathrm{PVC} = I + C_{\mathrm{omr}}\left[\frac{1+i}{r-i}\right]\cdot\left[1-\left(\frac{1+i}{1+r}\right)^{t}\right] - S\left(\frac{1+i}{1+r}\right)^{t} \quad (10)$$

Table 4 presents the final value of PVC (€) and energy cost (€/kWh) related to the three studied wind turbines.

8. Conclusion

As a conclusion of this paper, the following points are highlighted:

I. SJC region has a low level of wind resources, when compared with other Brazilians already investigated by the authors [29]. The wind speed mean (V) of 4.74 m/s and 5.31 m/s and wind power density (P/A_T) of 103 W/m^2 and 145 W/m^2 in the height of 25 m and 50 m respectively, may be used to support hybrid system for small uses.
II. The predominant wind direction to southeast also impact positively for future wind energy prospection.
III. The air average temperature of 24.46 °C at 25 m and 24.25 °C at 50 m has a strong impact on the air density value: 1.089 kg/m^3 and 1.114 kg/m^3 (25 m and 50 m respectively) instead of 1.225 kg/m^3 (WAsP default value) given and reduction in the final power energy calculated in the order of 13%.
IV. The average values of wind speed (V) of 4.76 at 25 m and 5.36 m/s at 50 m height and scale parameter (A) of 5.4 at 25 m and 6.0 at 50 m are strong correlated, that confirm correct use of Weibull distribution and the assumption that the Weibull scale parameter can be used to define the wind speed average value.
V. Weibull shape parameter (K) value of 2.54 and 2.59 from 25 m and 50 m respectively does not allow the use of Rayleigh distribution to characterize the wind speed distribution in SJC region.
VI. Beside the fact that the SJC region presents a low wind resources potential, the energy cost, 0.046 €/kWh in the best scenario, is inferior to the maximum energy purchasing price offered by Brazilian government program PROINFA – 0.087 €/kWh.
VII. The results of wind turbines simulated at 25 m, represent the best scenario with a C_f of 14.5% by using low wind turbines powered rated.
VIII. The precision and quantity of data from SONDA project become the final results reliable.
IX. The WAsP program shows robust and reliable tool to make wind characterization and wind energy potential assessment.

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